Discovery of Electronic Organization in High-T_c Superconductors

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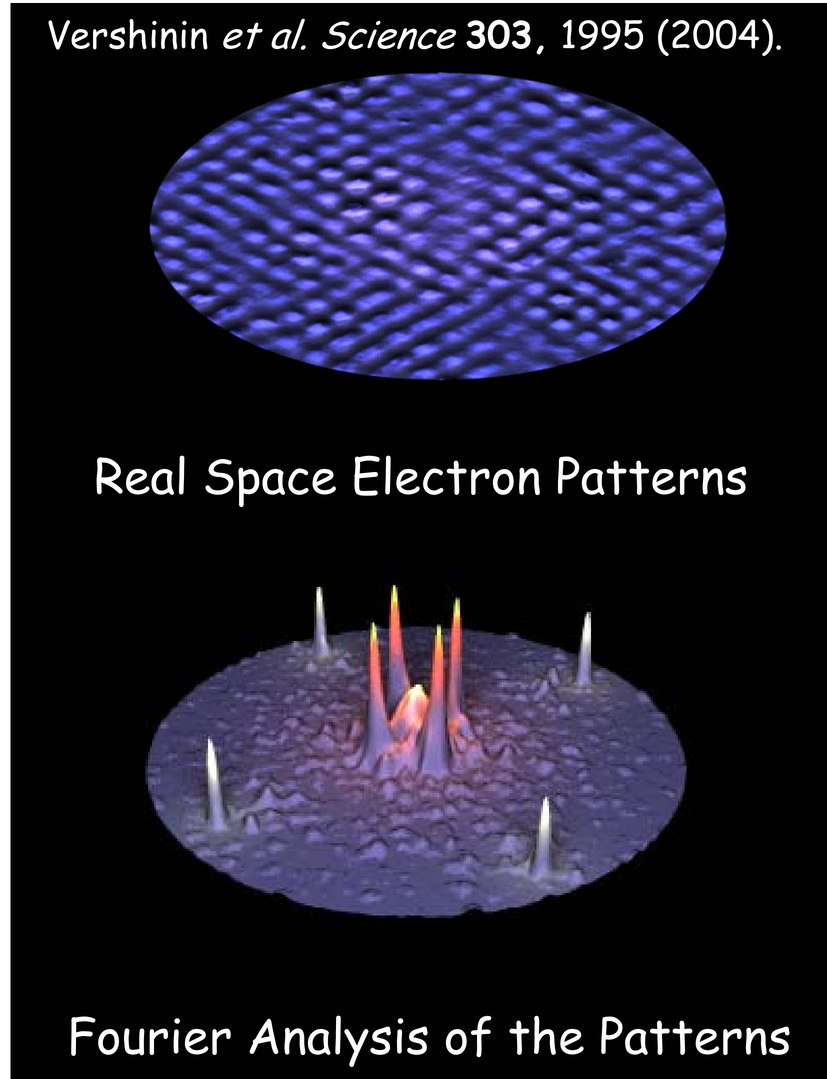
For more than a decade, the physics community has been baffled by high temperature superconductivity in the copper oxides. A large piece of the puzzle has been to understand how superconductivity is destroyed when the material are heated up. At elevated temperatures, above transition temperature, the cuprates do not behave like ordinary metals—making them even more complicated. In a recent ground-breaking experiment, published in *Science*, we have performed the first atomic-scale mapping of the electronic states in the unusual non-superconducting state of a cuprate superconductor. These experiments show that the electrons in these compounds form spatial patterns when they are not superconducting. This organization can be seen in maps of electronic states and takes a form of a checkerboard pattern with a periodicity close to four Cu-Cu lattice spacing. Real space patterns have been long predicted for electrons in the cuprates as result of anti-ferromagnetic correlation between electrons' spin and the Coulomb forces due their charge. Cooling the samples into the superconducting state, we find that these fixed patterns to disappear. The implication of our findings is when heated up the coherent dance of electrons in the superconducting state is replaced by their "crystallization" into real space patterns. These two electronic tendencies are competing in the cuprates and the one of the causes of their complex behavior.



Top: Mapping the electron wavefunction with the STM in the pseudogap reveals real space organization. Bottom: Fourier analysis of real space maps unveils the wavevector of charge organization . Work reported in Science February 2004.

Superconductivity, the ability to carry electrical current without resistance, has been studied for almost a century. The discovery of superconductivity in ceramic oxides in the late 1980's at temperatures above liquid nitrogen revolutionized the study of superconductivity. Since then the mechanism of superconductivity and the unusual electronic properties of these materials have been a mystery. Gaining understanding of these materials will not only be a major milestone in theory of electronic behavior in materials, but also has the potential to impact the search for even higher temperature superconductors as well as their applications in electronics. The work carried out in this program show that when heated, the orderly superconducting dance of electrons in these unusual superconductors is replaced, not by randomness as might be assumed, but by a distinct type of movement in which electrons organize into a checkerboard pattern. The experimental findings imply that the two types of electron organization, coherent motion required for superconductivity and spatial organization, are in competition in the copper oxides – an idea that may break the logjam on the mystery of high-temperature superconductivity.

Nanoscale Manipulation of Electronic States in Molecular Conductors

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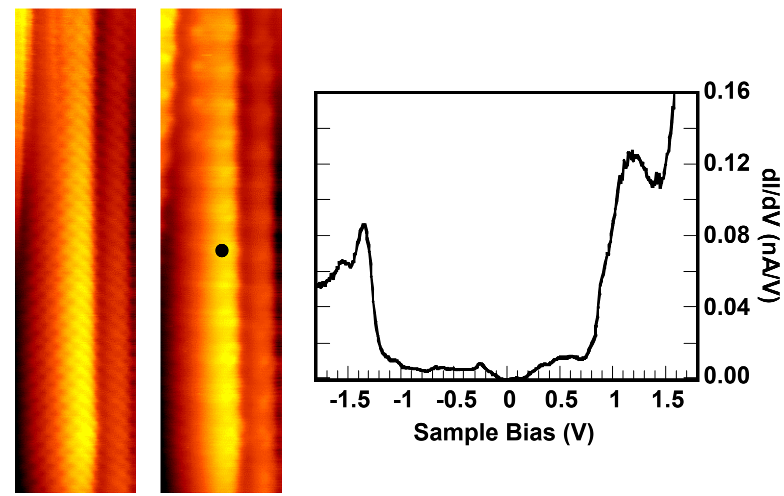
One of our major breakthroughs under NSF support has been to demonstrate that the electronic properties of carbon nanotubes (SWNT) can be selectively modified by the encapsulation of molecules inside their hollow core. These new class of one-dimensional materials, so-called nanoscopic peapods, have been investigated using state-of-the-art scanning tunneling microscopy. Detailed atomic-scale spectroscopic and imaging measurements have been used to unravel the role of encapsulated molecules (in this case C60) and their interactions with the nanotube cage. Modeling of the experimental results strongly suggest that the encapsulated molecules are electronically linked via the one-dimensional electronic states of the nanotube. During the last year, we have developed the ability to move the position of single C60 molecules with the STM inside the SWNT. We have focused on investigations of metallic peapods (right figure), which have modulated electronic states in one-dimension, yet they exhibit spectra similar to those of metallic nanotubes. In addition in collaboration with Prof. Goldhaber-Gordon at Stanford University we have began investigating transport measurements of these novel one dimensional systems.



Real space imaging of electron waves a nano-peapod along with tunneling spectroscopy measurements. The image on the left is occupies and the one on the right is the unoccupied electronic states of the peapod. While the conductance in the spectra at low voltages is low, it is still finite down to very low energies indicating metallic-like behavior.

Outreach Activities

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Brief summary of outreach activities:
The work on high-Tc superconductors will be featured in the September issue of Physics Today. Work carried out under this grant on nanoscopic peapds has been featured in a number of popular news stories in general science magazines like Scientific American, or in popular news magazines such as Wired Magazines. These stories are perhaps the only way the general public are broadly made aware of research nanotechnology. Furthermore, I have given several talks and conducted tours of my laboratory for undergraduate and high school students.

Educational (overall in my laboratory):
2 undergraduates (NSF-supported),
5 grad students (2.5 NSF-supported),
1 post-doc.